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# A Pilot Study of Shoulder Trauma Produced by Lateral Impacts

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## ABSTRACT

*The objective of this research was to analyze and document the response characteristics of the shoulder to lateral impacts. The need for this data was heightened in the late 1990's with the creation of side impact airbags, sport utility vehicles, harmonization of side impact standards, and the questioning of the measurement capabilities of the dummies used in evaluating these systems. A pneumatic impacting ram was employed in carrying out eight lateral impacts to four unembalmed human cadavers. The cadavers were instrumented with tri-axial accelerometer blocks at ten locations in the shoulder regions. The bony structures instrumented included the sternum, the first thoracic vertebra (T1), clavicles and scapulae. The accelerometer mount used on T1 was developed to decrease bleeding during the instrumentation phase. The output from the accelerometers was utilized to calculate impact forces and to examine the movement of the instrumented structures. Photographic targets were inserted into the accelerometer blocks, thus permitting image analysis of the shoulder component displacement. Autopsies were conducted and x-rays and magnetic resonance images were taken to document trauma that occurred as a result of lateral impact to the shoulder regions. Autopsies revealed that, in all cases, looseness of sterno-clavicular joints occurred. Three of the four cadavers showed a fracture of the right and or left distal clavicle. The documented results of the first eight impacts will be used to determine the test procedures for additional lateral impacts.*

## BACKGROUND

When the International Standards Organization (ISO) revised the biomechanical basis for the assessment of crash test dummy shoulder biofidelity requirements in May of 1997, they relied primarily upon two research reports. The first, a set of three lateral pendulum impactor tests, were conducted by researchers of the Association Peugeut-Renault (APR). From these three tests, a normalized $50^{th}$ percentile male shoulder response versus time history was established (Road Vehicles, 1997). The second, sled tests conducted by Wayne State University, were used by ISO/TC22/SC12 Working Group 5 to establish normalized shoulder plus thorax impactor force versus time histories. These tests also led to a proposed response corridor for an 8.9 m/s padded wall impact (Irwin, 1994;

Road Vehicles, 1997). Both research groups used non-embalmed cadavers in their research. Since the number of subjects used in these studies was limited, further study of the response of shoulder elements to a lateral impact seemed appropriate.

## METHODS

In the trauma laboratory, four unembalmed fresh cadavers, less than 48 hours post mortem, were subjected to separate impacts to the right and left shoulders. All testing was conducted in compliance with NHTSA Order 700-4, and was approved by The Ohio State University Biomedical Sciences Human Subjects Review Committee. Prior to impact, each cadaver was washed with a 10% bleach solution and inspected for evidence of existing or prior injuries to the shoulder girdles and sternum. Anthropometric measurements of each subject were also recorded. The cadaver was transported to the Magnetic Resonance facility where radiographs (X-rays) and magnetic resonance images (MRIs) of both shoulder regions, the sternum, and the first thoracic vertebrae were made.

### Instrumentation

The cadavers were then transported back to the trauma laboratory where triaxial accelerometer mounts were affixed to them. The mounts were positioned on ten locations throughout the shoulder region. The bony structures instrumented included the sternum, both the right and left acromion processes, both inferior angles of the scapulae, the lateral and medial extremes of each clavicle, and the first thoracic vertebra (T1). Three different mounting techniques were designed to securely fasten the accelerometer mounts to the boney sites while minimizing damage to the cadaver that could affect motion during impact.

The triaxial mounts located on the sternum, both the right and left acromion processes, and both inferior angles of the scapulae were anchored using screws. The mount on the inferior angle of the scapula along with the mount on the acromion process of the scapula allows for the movement of the scapula to be recorded during impact. The mounts were drawn tight against the bone using two standard one inch drywall screws.

FIG 1. Triaxial Accelerometer Mounts on the Lateral and Medial Thirds of the Clavicle

The accelerometer mounts positioned on the lateral and medial extremes of each clavicle were secured using plastic wire ties, see FIG. 1 below. The base of each mount was curled up on the end to keep the mount from slipping out from under the wire ties during impact. The position of the accelerometer mounts on the lateral and medial thirds of each clavicle was important in two regards. First, the output from the accelerometer mounts defined the movement of the clavicle during the lateral impact. Second, the output from the medial mount along with the output from the sternum mount monitored movement at the sterno-clavicular joint. Likewise, the outputs from the lateral end mount and the acromion process mount provided information on movement at the acromio-clavicular joint.

The triaxial accelerometer mount used on T1 was developed to decrease bleeding during the testing procedures. The design of the mount, similar to a thimble, allowed for it to slide over the top of the spinous process, see FIG. 2 below. A standard two inch drywall screw was tightened into the spinous process through the end of the mount, while two set screws were used on the sides of the mount to limit any rotation during impact.

FIG. 2. Triaxial Accelerometer Mount on the First Thoracic Vertebrae


FIG. 3. Cadaver Positioning on the Impactor Seat

*Pre-Test.* Following instrumentation, the cadaver was dressed in a suit of blue thermal underwear. The hands and feet were enclosed in white socks, and the head and neck were covered with a hood of thermal underwear, thus eliminating the possibility of identification of the donor. After the cadaver was suited for testing, the cadaver's upper limbs were exercised through their range of motion to eliminate rigor mortis. The subject was then positioned on the impactor seat with the center of the ram in line with the approximate center of the gleno-humeral joint (FIG. 3).

Photographic target pins were inserted into the triaxial accelerometer mounts after the cadaver was positioned. The purpose of the photographic pins was threefold. First, the pins enabled positioning measurements of each accelerometer mount to be recorded for subsequent analysis. Secondly, the angles of the photographic pins were measured to determine how far off axis each accelerometer was pointing prior to impact. Finally, the photographic pins were used to support camera targets, see FIG. 3. The movement of these targets during impact was tracked using two high speed digital cameras.

Once the cadaver was positioned and all photographic pin measurements were taken, the first lateral impact to the shoulder was conducted. A 22.86 kg pneumatic impacting ram was used to impact the shoulder at a constant velocity. The impacting surface, 8 in. by 6 in., was covered with Arcel 1.65 density padding. Following the first impact, the impactor seat, lighting, and digital cameras were rotated in preparation to impact the other shoulder of the cadaver. The impacted shoulder of the cadaver was palpated to check for fractures in the shoulder region. If a bone was believed to be fractured, the velocity for the second impact was set to be less than that used in the first impact. If fractures were not evident, the velocity was increased. After repositioning the cadaver and retaking the photographic pin measurements, the second impact was conducted.

*Post-Test.* Following the completion of the sequence of impacts, the shirt and all of the instrumentation was removed from the cadaver. When this was finished and it was ascertained that there was no residual metal remaining at the instrumentation sites, all incisions necessary for mounting instruments were sutured or taped closed. The cadaver was taken back to the Magnetic Resonance facility where radiographs and MRIs were retaken. These images were used to visualize, identify, and record any injuries which occurred due to the impacts. The autopsy was completed within two days and the findings were recorded.

## RESULTS

The physical statistics from the four test subjects are shown in Table 1. The table reveals that three of the four test cadavers were female and the average age of the subjects was 80 years. However, based on weight and height alone, cadaver number W 2009 could be categorized with the male subject as an approximate $50^{th}$ percentile male. Cadaver numbers W 1009 and O 4009 were approximate $5^{th}$ percentile female subjects. Table 1 also displays the impact velocity for each test, and whether the impact was to the right or left shoulder of the subject. The impact velocities ranged from 4.04 m/sec to 6.84 m/sec. The side of the cadaver selected for the initial impact alternated throughout the four test subjects. This technique was implemented to ensure two initial impacts to the right shoulder and two to the left shoulder and to eliminate a potential source of systematic bias in the test sequence.

Table 1: Cadaver Details And Test Conditions

| Cadaver Data | | | | | Test Conditions | |
|---|---|---|---|---|---|---|
| Cadaver # | Sex | Age | Height (cm) | Weight (kg) | Impact Side | Impact Vel. (m/sec) |
| W 1009 | F | 84 | 157 | 47.63 | Left | 5.30 |
| | | | | | Right | 6.84 |
| W 2009 | F | 73 | 160 | 80.74 | Right | 5.13 |
| | | | | | Left | 4.14 |
| W 3009 | M | 82 | 177 | 72.57 | Left | 4.62 |
| | | | | | Right | 4.89 |
| O 4009 | F | 79 | 155 | 49.90 | Right | 4.64 |
| | | | | | Left | 4.04 |

The preliminary test findings were grouped into two sets of results. The first set of results was from the initial impact to each cadaver. The second group of results came from the second impact to each cadaver. The issue of separating the results arose from the possibility that the initial impact might have damaged the structure of the non-impacted shoulder. This possible damage could have led to erroneous test results when the second shoulder was impacted.

The force that the impacted shoulder received from the impactor, for the first impact of each subject, is shown in FIG. 4. The input force was calculated from the accelerometer mounted on the ram of the impactor. Figure 4 reveals that the input forces for the approximate $5^{th}$ percentile female subjects (1009 and 4009) were very similar, as were the input forces for the male subject and the larger female subject (2009 and 3009).

FIG. 4. Input Force from Pneumatic Ram for $1^{st}$ Set of Shoulder Impacts

The y-axis displacement between the impacted acromion process and the sternum, for the first set of shoulder impacts, is displayed in FIG. 5. Noted beside each displacement curve in FIG. 5 is the velocity of the ram at the time of impact. The displacement of the shoulder was calculated through analysis of the high speed digital imagery. FIG. 5 shows that the second subject, 2009, had the largest displacement of the shoulder, due to the high velocity of the ram at impact. Due to the impactor not achieving a constant velocity and because of preexisting degenerative changes of the subject, cadaver 1009 recorded less displacement at a faster impact velocity. These degenerative changes also explain why the shoulder remained displaced instead of recoiling like the shoulders of the other subjects. The male subject, cadaver number 3009, showed less displacement than subject number 4009, a fifth percentile female, even though they were impacted at similar velocities. Many of the displacement curves revealed a negative displacement before the shoulder was compressed into the sternum. The high speed images revealed that on these subjects, the sternum jolted away from the impact before compression began, due to the force being transmitted through the shoulder structure.

The input forces for the second set of shoulder impacts are displayed in FIG. 6. Once again, the impactor ram for the first cadaver (1009) did not obtain free flight, causing the input force to initially register a negative value. The input forces to the shoulders of the other subjects were very similar, with the male subject receiving the greatest force.

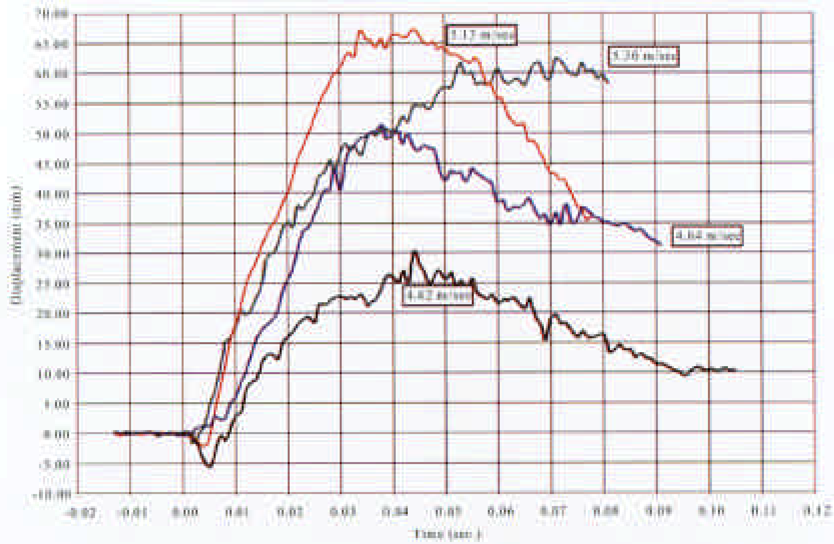

FIG. 5. Y-Axis Displacement Between Sternum and Impacted Acromion Due to 1st set of Impacts

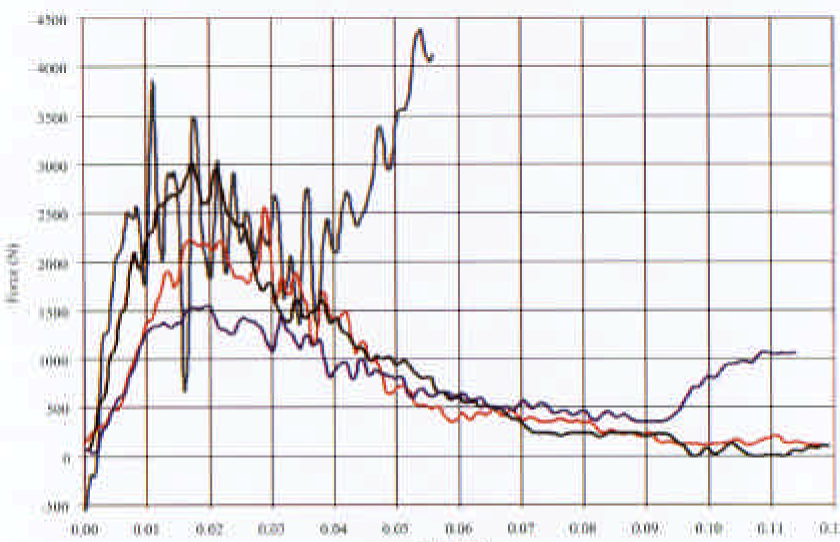

FIG. 6. Input Force from Pneumatic Ram for 2nd Set of Shoulder Impacts

The y-axis displacement between the impacted acromion process and the sternum, for the second set of shoulder impacts is shown in FIG. 7. As in FIG. 5, noted beside each displacement curve in FIG. 7 is the velocity of the ram at the time of impact. The effect of the preexisting degenerative changes on the first subject's (1009) shoulders was again evident in the displacement curve. The first cadaver's displacement curve revealed the largest displacement of all of the tests and failed to show the shoulder recoil after impact. Cadaver numbers 2009 and 4009 showed similar displacements, which coincided with their similar impact velocities. Once again, the male subject (3009) recorded the least amount of shoulder displacement.

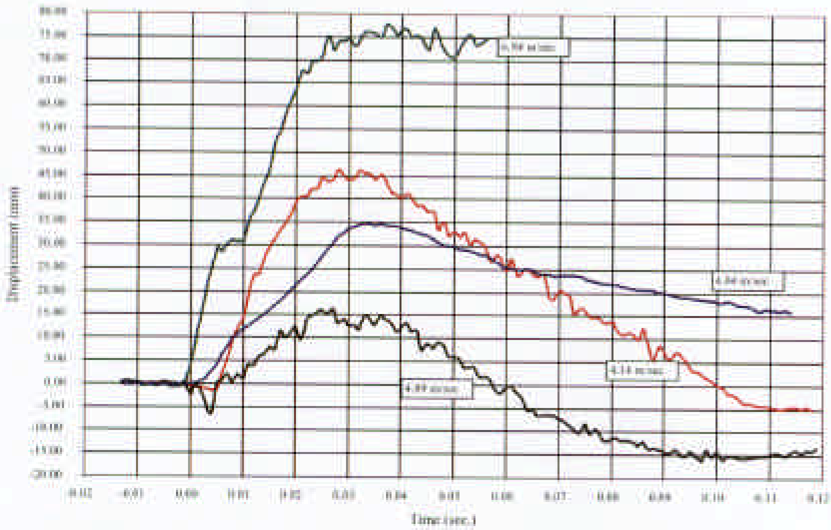

FIG. 7. Y-Axis Displacement Between Sternum and Impacted Acromion Due to 2[nd] set of Impacts

## Autopsy/Radiograph/MRI Results

The injuries that were sustained during the impacts are summarized in Table 2. The injuries were recorded from autopsy results, radiographs, and magnetic resonance images. It is important to note that to date, the radiograph and MRIs from cadavers 3009 and 4009 have yet to be read. Therefore, the injuries stated for these cadavers in Table 2 were recorded from autopsy results only.

Table 2: Injuries Sustained During Impact

| Test | Side | Muscles | Tendons | Joints | Bones |
|---|---|---|---|---|---|
| 1009 | Right | N | n | loose sternoclavicular | fx - distal clavicle; coronal fx acromion |
| | | | | Loose 2[nd] costochondral | ribs fx - 3,4,5,6 |
| | Left | N | n | loose sternoclavicular | fx - distal clavicle; cortex fx acromion |
| | | | | loose 2[nd] costochondral | ribs fx - 5,6,7 |
| 2009 | Right | N | n | loose sternoclavicular | fx - distal clavicle; ribs fx - 3,4, ?5 |
| | Left | ? post. deltoid intramural fiber trs | n | ? glenohumeral lig. tr | ribs fx - 3,4,5 |
| | | | | ant. labral displacement | |
| **Autopsy Data Only** | | | | | |
| 3009 | Right | N | n | loose sternoclavicular | n |
| | Left | N | n | loose sternoclavicular | n |
| 4009 | Right | N | n | loose sternoclavicular | fx - distal clavicle; ribs fx - 3,4 |
| | Left | N | n | loose sternoclavicular | fx - distal clavicle; ribs fx - 4,5 |

LEGEND: fx - fracture tr - tear n - none ? - probable

The results revealed that the most common injury sustained was a broken clavicle. In five of the eight impacts, the clavicle was fractured distally, 1.5 to 3.0 cm from the acromio-clavicular joint. It is important to note that the fractures were not located at the instrumentation sites.

Another frequent injury sustained during impact was looseness of the sterno-clavicular joint. This instability is thought to be due to force transmission through the clavicle prior to the fracture of the clavicle. The table also shows that the first cadaver had several fractured ribs. This was due to impacting the first subject below the center of the glenohumeral joint. Subsequent test impact locations were in better alignment with the glenohumeral joint.

The injuries are summarized in Table 3 according to the method of detection (autopsy, x-ray, or MRI). These results show that the MRI documents both hairline fractures and soft tissue injuries that the autopsy and x-rays do not reveal.

Table 3: Comparison Of Injury Findings

| Test | Side | Autopsy | X-Ray | MRI |
|---|---|---|---|---|
| 1009 | Right | fx - distal clavicle | fx - distal clavicle | fx - distal clavicle |
| | | loose sternoclavicular jt. | | loose sternoclavicular jt. |
| | | loose 2nd costochondral jt. | | loose 2nd costochondral jt. |
| | | | coronal fx acromion | coronal fx acromion |
| | | | | ribs fx - 3,4,5,6 |
| | Left | fx - distal clavicle | fx - distal clavicle | fx - distal clavicle |
| | | ribs fx - 5,6,7 | ribs fx - 5,6,7 | ribs fx - 5,6,7 |
| | | loose sternoclavicular jt. | | loose sternoclavicular jt |
| | | loose 2nd costochondral jt. | | loose 2nd costochondral jt. |
| | | | cortex fx acromion | cortex fx acromion |
| 2009 | Right | fx - distal clavicle | fx - distal clavicle | fx - distal clavicle |
| | | loose sternoclavicular jt. | | |
| | | | ribs fx - 3,4 | ribs fx - 3,4, ? 5 |
| | Left | | ribs fx - 3,4,5 | ribs fx - 3,4,5 |
| | | | | ? glenohumeral tr |
| | | | | ant. labral displacement |
| | | | | ? tr intramural fibers of deltoid mm. |

LEGEND: fx - fracture tr - tear n - none ? - probable

## CONCLUSIONS

A few important conclusions can be drawn from these preliminary tests. First, the most common injuries sustained during lateral shoulder impacts were fractures of the distal clavicle and the instability of the sterno-clavicular joint. Secondly, the injury threshold impact velocity appears to fall between 4 to 5 m/sec, a slower velocity than reported in previous research. Third, magnetic resonance images give a more detailed analysis of soft tissue damage, which is vital in the shoulder region. Finally, completing these four tests have helped to clarify and refine the testing protocols and procedures for future shoulder testing.

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## APPENDIX A

### Significant Autopsy Findings

#### Cadaver W 1009

*Muscles.* Preexisting degenerative changes in both the right and left rotator cuff (supraspinatus, teres minor, infraspinatus, and subscapularis) muscles were identified at their attachments to the glenohumeral capsule and upper end of the humerus. The tendon of the subscapularis seemed to be intact. There were no apparent contusions or tears of muscles around the shoulder due to trauma of impact, and the tendons of the biceps and triceps brachii were apparently intact.

*Joints.* There were no ligamentous tears identified. Both right and left sternoclavicular joints were loose as were the costochondral joints of both right and left $2^{nd}$ to $6^{th}$ ribs.

*Bones.* The lateral most (distal) ends of both clavicles were fractured just medial to the acromio-clavicular joint. There were no other fractures of the shoulder girdle or sternum, but the left humeral head was markedly eroded due to preexisting degenerative changes. Right ribs 2 to 6 were fractured but not displaced. There were no easily identifiable left rib fractures.

#### Cadaver W 2009

*Muscles.* There were no muscle or tendon injuries to either the right or left side.

*Joints.* There was moderate looseness of the right sterno-clavicular joint but no evidence of ligamentous tearing. No injuries to any other joints were found.

*Bones.* The right clavicle was fractured at its distal end, just medial to the acomio-clavicular joint. T1 was intact except for the absence of its spinous process which was removed to seat the mount. No rib fractures were apparent.

#### Cadaver W 3009

*Muscles.* No muscle or tendon tears were noted.

*Joints.* Both sterno-clavicular joints were loose, but there was no visible evidence of ligamentous tearing.

*Bones.* There were no new fractures of either clavicle, but the left clavicle exhibited an old well-healed fracture at the junction of its lateral and middle one third. No other fractures were discernable at autopsy.

#### Cadaver 0 4009

*Muscles.* No muscle or tendon tears were noted.

*Joints.* Both sterno-clavicular joints were loose, with the left looseness being the most marked. There were no apparent ligamentous tears in any of the shoulder girdle joints.

*Bones.* Both clavicles were fractured at their distal ends, the right 2.5 cm and the left 2 cm medial to the acromio-clavicular joint. Ribs 3 and 4 on the right, and 4 and 5 on the left, were fractured at the midclavicular line.

**Significant Radiographic and Magnetic Resonance Findings**

**Cadaver W 1009**

*Pre-test.* Full thickness tears of the right and left supraspinatus, infraspinatus, and teres minor muscles were present, but only a chronic tendonitis was found in the subscapularis. Both biceps brachii tendons appeared attenuated. The labra of both sides were abnormal in their superior, anterior, and posterior extents. There was evidence of degenerative changes in the glenohumeral, acromio-clavicular, and sterno-clavicular joints. No fractures were seen in any view.

*Post-test.* Findings revealed the previously described preexisting degenerative changes, but did not identify looseness of the sterno-clavicular joints. The right 2$^{nd}$ costo-vertebral joint appeared dislocated. There were no other ligamentous, tendon, capsular, or muscle tears present. Fractures of the distal ends of both right and left clavicles were evident. The right clavicle was fractured 1.5 cm medial and the left just medial to the acromio-clavicular joint. There were non-displaced fractures of both acromia. The right acromial fracture was coronal while that of the left was simply a disruption of its superior cortex. Right ribs 3 through 6 and probably 7, and left 5 through 7, were fractured at the midaxillary line. T1 vertebrae was not fractured, but the spinous process was removed to mount the accelerometer.

**Cadaver W 2009**

*Pre-test.* Both the right and left shoulders exhibit supra and infraspinatus muscle tendonitis. The right had some bursal side tear, probably resulting from impingement. The glenohumeral joints appeared normal, but the right showed some anterior tearing and posterior labral degeneration with some joint effusion. Both right and left sterno-clavicular joints have some degenerative changes but there is no evidence of dislocation. Both right and left subacromial bursa also show some effusion. There are no fractures or dislocations present.

*Post-test.* No evidence of rotator cuff abnormality, except for the preexisting tendonitis in the supra and infraspinatus muscles. On MRI of the left shoulder, there is indication of some internal muscle fiber tearing or contusion in the posterior deltoid, which has not been observed in previous post impact films. Both the right and left glenohumeral articulations appear anatomic on radiographs. The right glenohumeral joint also appears anatomic on MRI, but the left glenohumeral joint shows evidence of humeral head inferior subluxation. This may have been permitted by some disruption of the anterior capsule and the glenohumeral ligament(s).

There is no evidence of any dislocation or ligament tear in either right or left acromio-clavicular or sterno-clavicular joints. The acromial processes were not fractured, but the radiograph of the right side shows a lucency which could represent a cortical disruption. However, MRIs are inconclusive, indicating that such a cortical fracture is only possible. The left coraco-clavicular ligament is intact in spite of some nearby instrument induced tissue damage. Preexisting labral tears were unchanged, except that on the left there was some anterior labral displacement.

Both right and left distal clavicles were fractured 1.5 cm medial to the acromio-clavicular joint. The right was displaced anterior and superiorly. The left was not displaced. Ribs 3 and 4 were fractured laterally on both sides, as was rib 5 on the left. Right ribs 5 and possibly 6 were fractured posteriorly. There was no displacement at any rib fracture site.